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Bedrock Depth Mapping of the Coast South of İstanbul: Comparison of Analytical and Experimental Analyses

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Abstract: Local S-wave velocity-depth profiles and bedrock depth distribution are key factors in assessing seismic hazard and earthquake ground motion characteristics since they allow determination of the amplification potential of geological formations overlying bedrock. In this study, an empirical relationship between the thickness of Tertiary–Quaternary sediments (hereafter referred as cover) overlying Palaeozoic bedrock and their resonance frequencies was calculated for the İstanbul region and the bedrock depth distribution beneath the city was presented. The relationship was investigated by comparing transfer functions obtained from single station microtremor analyses and one-dimensional (1D) S-wave velocity profiles at sites where shallow velocity structure is known. Geotechnical data consisting of standard penetration test (SPT) blow counts and standard soil descriptions were evaluated from 15 boring sites and microtremor measurements were carried out. The bedrock depth of each site was determined by computing analytical transfer functions to fit the resonance frequency and the shape of experimental transfer functions. Based on those results, a relationship between the resonance frequency and the thickness of the cover was derived. Finally, the bedrock distribution beneath populated areas of İstanbul was obtained by applying the derived relationship to 86 strong-motion sites, where the resonance frequencies are known.

Key Words: site response, microtremor, resonance frequency, bedrock depth, İstanbul

İstanbul'un Güney Kıyılarının Temel Kayası Derinliği Haritalaması: Analitik ve Deneysel Analizlerin Karşılaştırılması

Özet: Bölgesel S-dalgası hızının derinlikle değişimi ve temel kayası derinlik dağılımı jeolojik formasyonların büyütme potansiyellerinin anlaşılması bakımından sismik tehlike ve deprem hareketi karakteristiklerinin tahmininde önemli rol oynamaktadır. Bu çalışmada İstanbul bölgesi için Paleozoyik temel kayası üzerindeki Tersiyer–Kuvarterner yaşlı tabakaların (bundan sonra örtü olarak adlandırılacaktır) kalınlığı ile rezonans frekansı arasında ampirik bir ilişki hesaplanmış ve şehrin temel kayası derinlik dağılımı sunulmuştur. Ampirik ilişki, mikrotremor analizleri ve tek boyutlu (1D) S-dalgası hız profillerinden elde edilen transfer fonksiyonlarının karşılaştırılması ile hesaplanmıştır. Bu amaçla bölgede var olan 15 kuyudaki standart penetrasyon testi (SPT) darbe sayıları ile standart zemin tanımlamalarından oluşan geoteknik veriler değerlendirilmiş ve kuyular civarında tek istasyonlu mikrotremor ölçümleri yapılmıştır. Her kuyu için temel kayası derinliği, analitik transfer fonksiyonların şekli ve rezonans frekansı arazi ölçümlerinden elde edilen transfer fonksiyonlarına uyum sağlayacak şekilde, hız-derinlik profillerine mühendislik kayası katmanının eklenmesi ile hesaplanmıştır. Bu hesaplamalardan rezonans frekans ile Paleozoyik temel kayası üzerindeki örtünün kalınlığı arasında ampirik bir denklem elde edilmiştir. Bu ampirik ilişkinin, rezonans frekansı bilinen 86 kuvvetli yer hareketi kayıt istasyonunda kullanılması ile İstanbul'da kentsel nüfusun yoğun olduğu bölgelerin altındaki temel kayası derinlik değişimi hesaplanmıştır.

Anahtar Sözcükler: zemin davranışı, mikrotremor, rezonans frekans, temel kayası derinliği, İstanbul

Introduction

The severe consequences of sediment amplification of ground motion have been well-known since the beginning of the 20th century. Numerous site response studies in earthquakes during the last three decades showed large concentrations of damage in specific areas overlain by soft sediments (e.g., Bard & Bouchon 1980; Kawase 1996; Wald & Graves 1998; Kudo *et al*. 2002). The most important parameters deduced from site response studies are the resonance periods of soil vibration and the amplification factors of ground motion in certain frequency ranges. Microtremor measurements offer an inexpensive and simple tool to determine resonance frequencies of sites. The horizontal to vertical spectral ratio (H/V) technique (Nakamura 1989) provides reliable estimates of resonance frequencies of sites, despite its inadequacy in estimating amplification (e.g., Bard 1999).

Recently, Ibs-Von Seht & Wohlenberg (1999) proposed that resonance frequencies in H/V spectra correlate well with the overall soil thickness, ranging from tens of metres to more than 1000 m. Delgado *et al.* (2000) confirmed the validity of the method comparing abundant geotechnical information and results of microtremor measurements available in Spain. They addressed limitations of the method as well. A practical application of the method was also performed by Parolai *et al.* (2002) and Hinzen *et al.* (2004) in the Cologne area of Germany.

Little is known about the site-effects and subsurface velocity structure information in İstanbul except in certain areas where microtremor measurements were performed (e.g., Kudo *et al.* 2002; Özel *et al.* 2002, 2004; Sorensen *et al.* 2006). In 2005, microtremor measurements were carried out at 100 Rapid Response (RR) strong motion stations spread throughout the city of İstanbul (Özel *et al.* 2006). Together with the usage of four near-field ($3<M_L<4.5$) event recordings at RR sites, resonance frequency distributions using the H/V Technique and relative site amplifications through Standard Spectral Ratio ((SSR), (Borcherd 1970) were estimated at 86 of 100 stations (Figure 1) by Birgören & Özel (2006). Those measurements showed that the resonance frequencies significantly vary between 0.44 Hz and 7 Hz within the city. Distribution of the resonance frequencies generally shows that sites along the coast line of the southwestern part of the city have very low values (0.44 – 1 Hz.) and frequencies increase from south to north, ranging up to about 4.6 Hz. Resonance frequencies shift to higher values at sites on the Asian side of the Bosphorus.

As part of a basic disaster prevention/mitigation project for İstanbul, the Japan International Cooperation Agency (JICA) team performed 48 deep and shallow borings ($h \leq 206$ m) to evaluate S-wave velocity structures underneath the city, especially on the European side where sedimentary formations of Tertiary–Quaternary ages exist (JICA & IMM 2002). The results were used to produce the distribution of S-wave velocity averaged to 30 m depth beneath the city, since only this information is required to estimate site-dependent design spectra for use in building codes (e.g., IBC 2006). However, average S-wave velocity in the uppermost 30 m only gives amplification information relating to 1D site effects and is insensitive to 2D and 3D site effects. Realistic strong motion estimations at sites located on thick soil deposits depend on a well-known subsurface structure modelling. Therefore, a correlation between bedrock depth obtained from borehole data and resonance frequencies obtained from the analysis of microtremor recordings may be used as a practical tool to get an outline of the subsurface structure, particularly in regions where subsurface geology is poorly known, such as İstanbul city.

The objective of this study is to derive an empirical relationship between the resonance frequencies obtained from the H/V Technique and the thickness of the cover, and generate a rough bedrock depth distribution beneath the İstanbul city. This information is critical for earthquake ground motion simulation studies since the city is the most populated area in the Marmara Region which is under earthquake threat, as indicated by several studies performed after the 1999 Kocaeli Earthquake (e.g., Parson *et al.* 2000).

Geological Setting

The northern, northeastern and central parts of İstanbul are dominated by Palaeozoic rocks, which are regarded as seismological bedrock due to their high S-wave velocity. The Palaeozoic basement consists of firm rocks of Ordovician (Kurtköy and Aydos formations), Devonian (Baltalimanı, Kartal, Trakya, Gözdağ, Dolayoba and Tuzla formations) and Carboniferous ages. The oldest Tertiary sediments lying unconformably on the Palaeozoic formations form the Middle Eocene to Early Oligocene Kırklareli formation. This sequence starts transgressively with a basal conglomerate and strata containing clay and coal, which are overlain by cream-coloured limy claystones and karstic reef limestones. The top of the formation comprises lithologies such as argillaceous limestone, marl and limy sandstone. Soft sediments are generally seen in the southwestern part of the city as shown in Figures 2 & 3. In this region, upper Miocene sediments such as the Çukurçeşme, Güngören and Bakırköy formations directly overlie the Palaeozoic bedrock (Okay 1986). Among them, the Çukurçeşme formation contains dense to very dense sand, silty sand, clayey sand, gravel and clay. The Güngören formation consists of fissured, highly plastic, thinly-laminated clays, and the Bakırköy formation comprises white, porous,

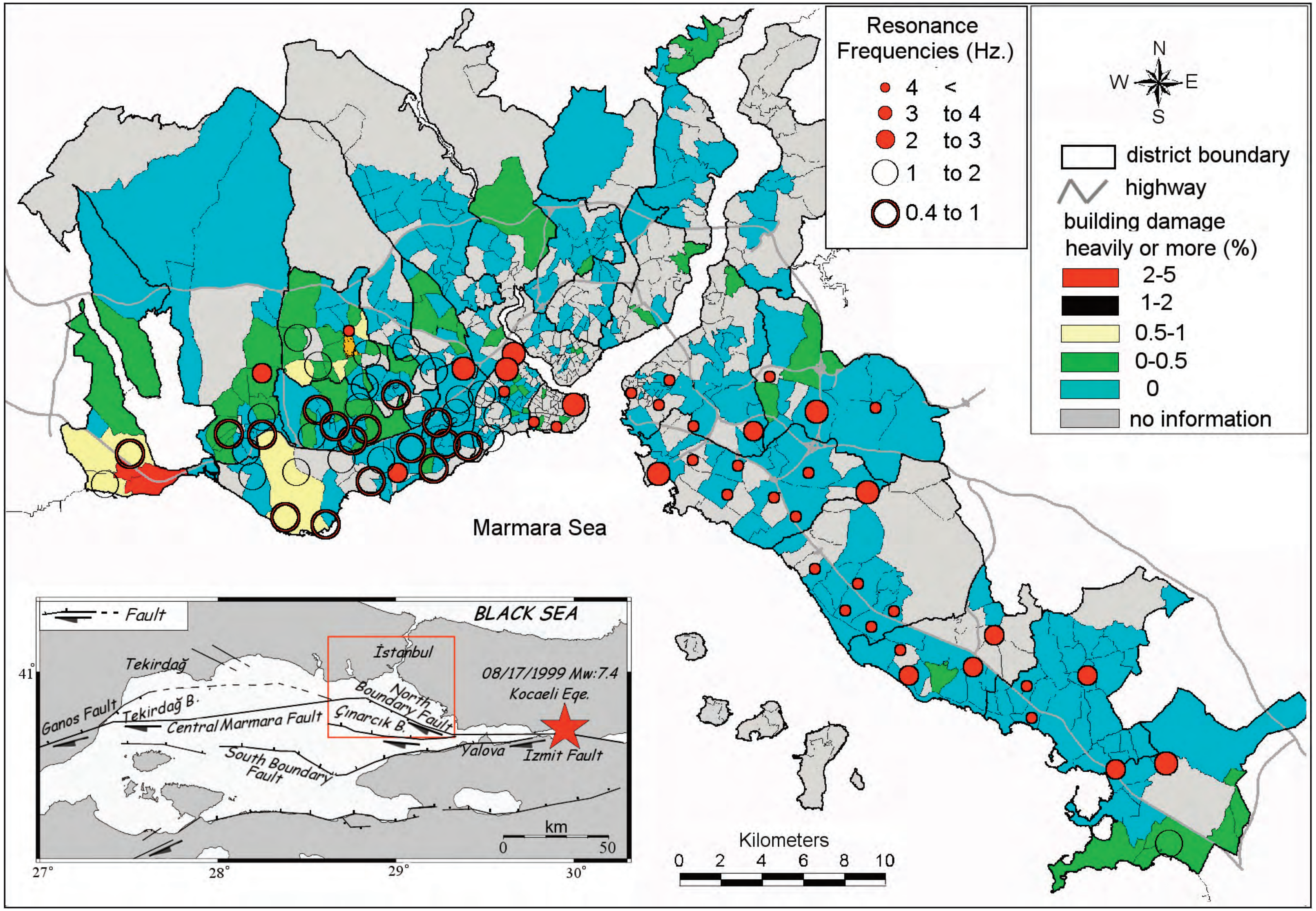

Figure 1. Resonance frequencies obtained from microtremor measurements at RR station locations (Birgören & Özel 2006) together with building damage distribution in İstanbul during the 1999 Kocaeli Earthquake (after İstanbul Governorate, personal communication 1999). Inset figure shows the active faulting map of the Marmara Region (redrawn from Okay *et al.* 2000).

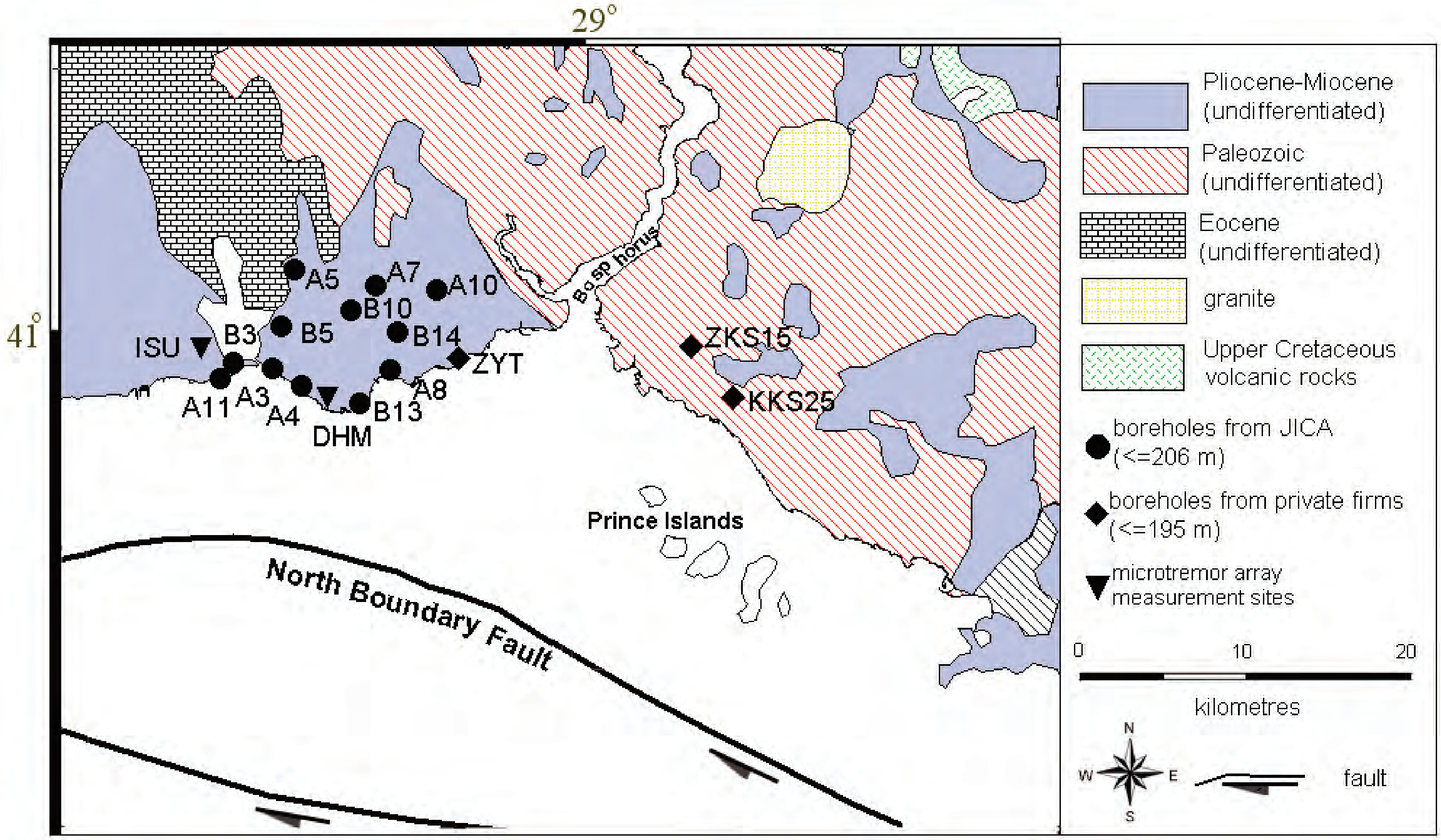

Figure 2. Simplified geological units of İstanbul and vicinity (after Okay 1986) together with locations of boreholes from which data were used to derive the resonance frequency-thickness relationship. The eastern part of the figure is improved by the recently prepared surface geology map of İstanbul (JICA & IMM 2002). Pleistocene and Quaternary deposits are not shown due to the scale limitation.

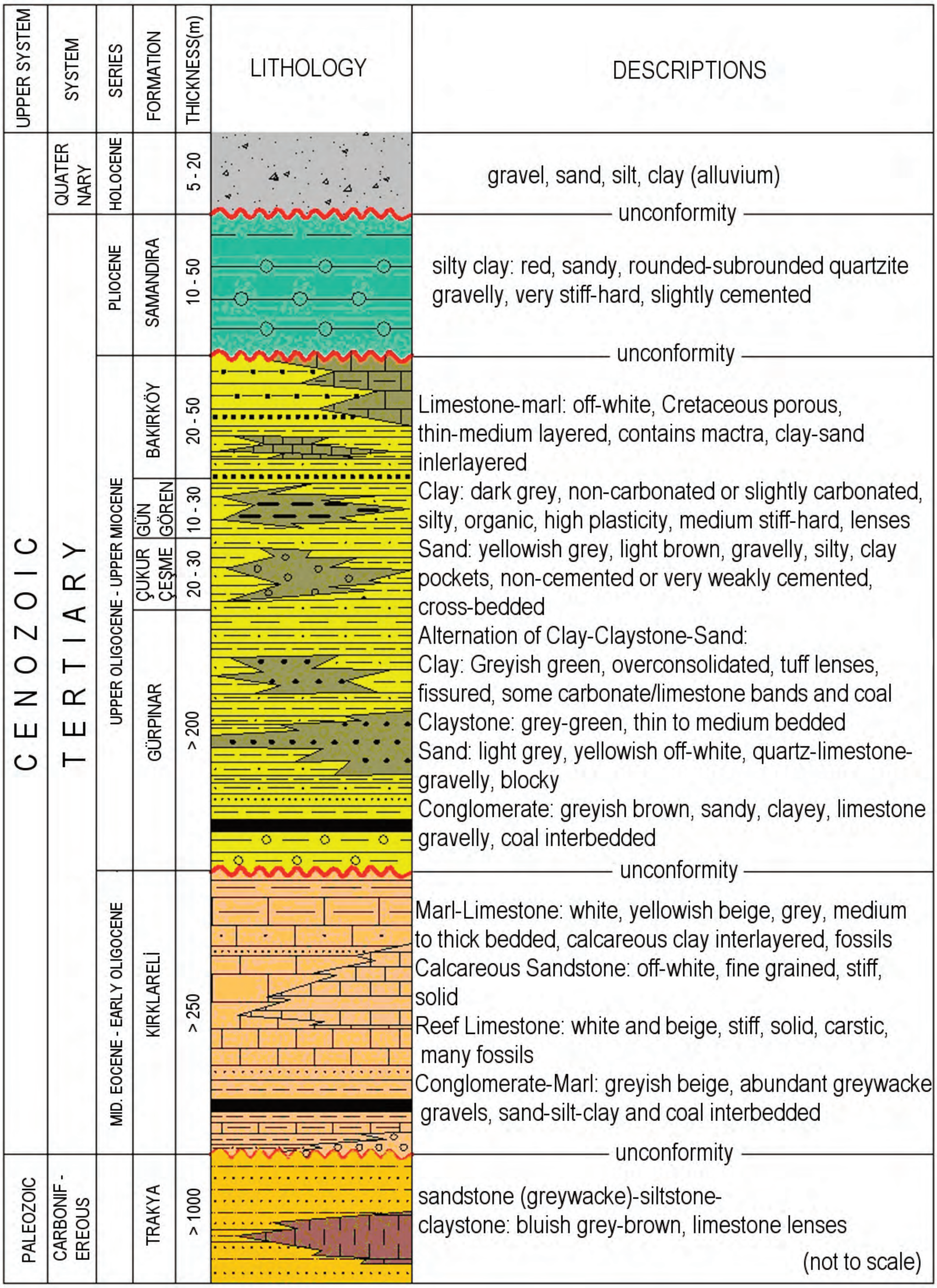

Figure 3. Stratigraphic section showing major lithostratigraphic units of the İstanbul area (after Yıldırım & Savaşkan 2003).

chalky, medium to hard limestone and subordinate clay. The Late Quaternary Kuşdili formation, consisting of clay, sand and mud, covers the southern shore of the Küçükçekmece Lake and the Golden Horn. Deposits of fluvial origin consist of gravel, sand, silt and clay (Yıldırım & Savaşkan 2003). The RR array covers geological settings ranging from alluvium to limestone/sandstone. However, detailed description of geological strata and near-surface velocity structures under stations are unavailable.

Microtremor Measurements

Single station noise measurements at 9 deep (h ≥ 87 m) boring sites and a microtremor array measurement site (ISU) located in the southwestern part of the city (Figure 2) were undertaken using a Guralp CMG6T type three-component broadband frequency digital seismometer. At 5 of those 9 sites measurements were simultaneously done with both the Guralp CMG6T and with Geosig GSR18 strong motion accelerographs equipped with Guralp CMG-5T sensors. To estimate resonance frequencies at 6 shallow (h ≤ 56 m) borehole sites, GSR18 recordings of RR stations, located close (< 250 m) to these borehole sites, and broadband seismometers were used. Microtremor measurements were carried out for about one hour at 100 Hz sampling rate.

The H/V Technique was used to obtain resonance frequencies of sites. To estimate resonance frequencies, all records were visually checked to avoid intensive artificial sources. Each record was divided into 40 s-time windows, and corrected for baseline. The Fourier Spectrum of each 40 s portion of noise recordings was computed after applying 10% cosine tapering. The root-mean square of the spectra from the two horizontal components was used as the numerator of the spectral ratio, and divided by spectrum of the vertical component to get the H/V ratio. This procedure was repeated with the remaining windows. The average H/V ratio of the whole windows was then smoothed using a low pass filter.

In general, resonance frequencies obtained from H/V ratios are instantly recognizable at most borehole sites (Figures 4–6). Peak frequencies of the H/V ratios at sites in the European side of the city are between 0.44–1.54 Hz. Resonance frequencies increase from south to north. KKS25 and ZKS15, both on the Asian side of the city, have resonance frequencies of 4.5 and 5 Hz, respectively (Table 2). These values are consistent with the findings of previous studies (e.g., Birgören & Özel 2006; Sorensen *et al.* 2006).

Soil Profile Modelling by 1D Site Response Analysis

Site response analyses were performed at 15 (9 deep and 6 shallow) borehole sites. At each one representative soil profiles (2 or 3 shallow layers overlying on a single stiff soil which can be considered as the engineering bedrock) were defined. Most of the deep boreholes failed to reach the engineering bedrock. Therefore a layer representing engineering bedrock deposits was included into each velocity profile, with S-wave velocity of 760 m/s. Beneath this layer, Palaeozoic bedrock with S-wave velocity of 2500 m/s was defined as a half space.

The basic properties of representative soil profiles such as total unit weight, thickness of layers, and S-wave velocities (*Vs*) were determined from both detailed borehole studies and in-hole PS-logging S-wave velocity measurements. Several procedures can be used to establish the *Vs* distribution with depth. Aside from measurements in the borehole, which were only available, several empirical correlations between SPT and CPT data and S-wave velocity can be utilized (e.g., Ohta & Goto 1978; Mayne & Rix 1995; İyisan 1996). Among them the correlation of the S-wave velocity with the SPT values seems to offer the best fit and the relation proposed by İyisan (1996) has been selected since it involves all soil types.

The variation of S-wave velocities with depth was determined by utilizing available SPT blow count numbers using the empirical relationship proposed by İyisan (1996) as follows

$$Vs = 51.5N^{0.516} \qquad (1)$$

where *N* is uncorrected standard penetration blow counts. In this study, the variations of SPT-N values with depth for formations in boreholes are given in Table 1. Representative S-wave velocities were determined for each layer using estimated S-wave velocities along boreholes.

Borehole sites were modelled by Shake91 (Schnabel *et al.* 1972; Idriss & Sun 1992), a one-dimensional site response program that propagates vertically incident S-waves from bedrock outcrop or half-space through a

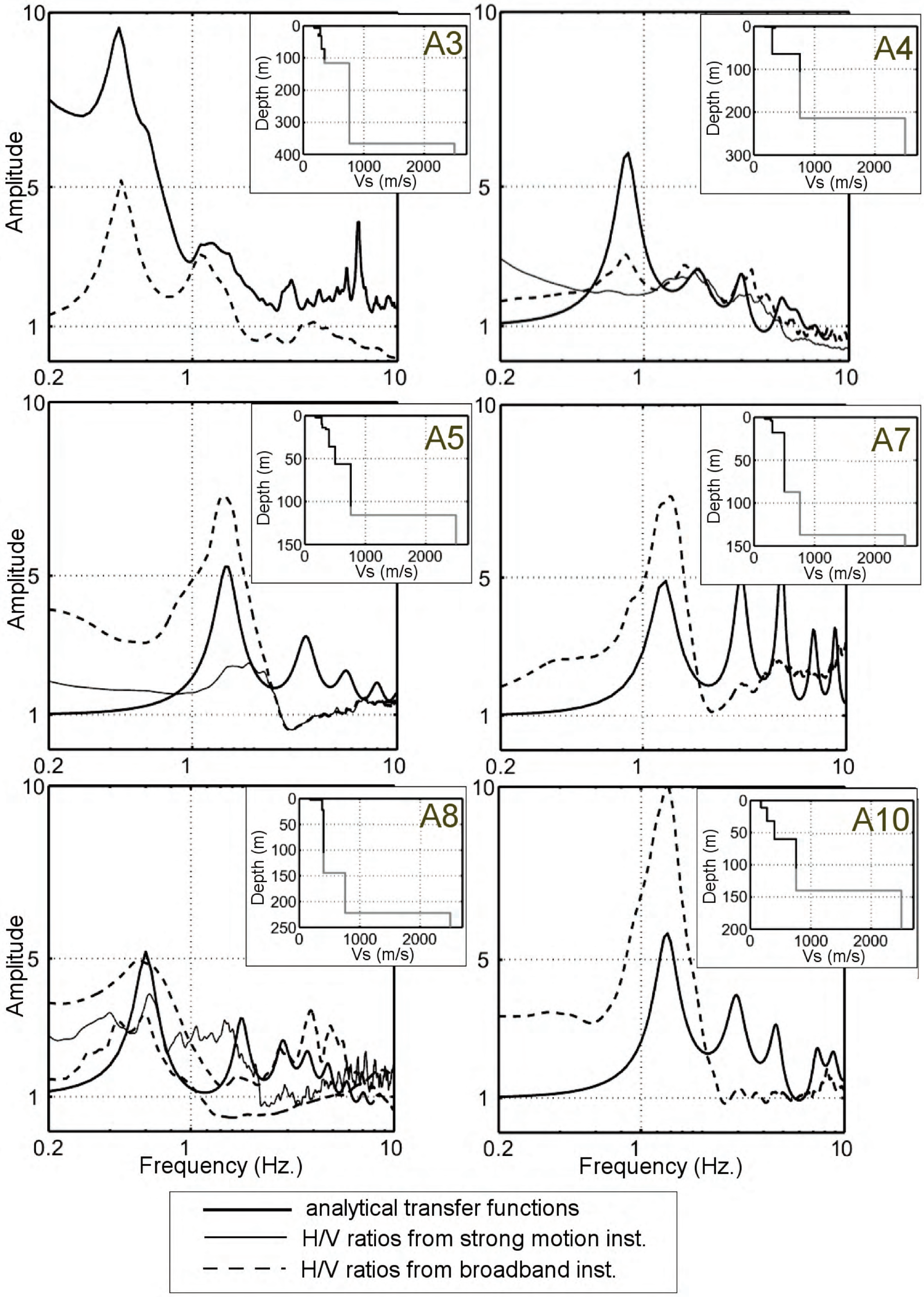

Figure 4. Comparison between H/V spectral ratios from microtremor measurements at A3, A4, A5, A7, A8, A10 sites. Inset figures show the 1D Velocity-depth profiles at the borehole locations. The dark line of the profiles shows the borehole results, and grey lines are calculated results.

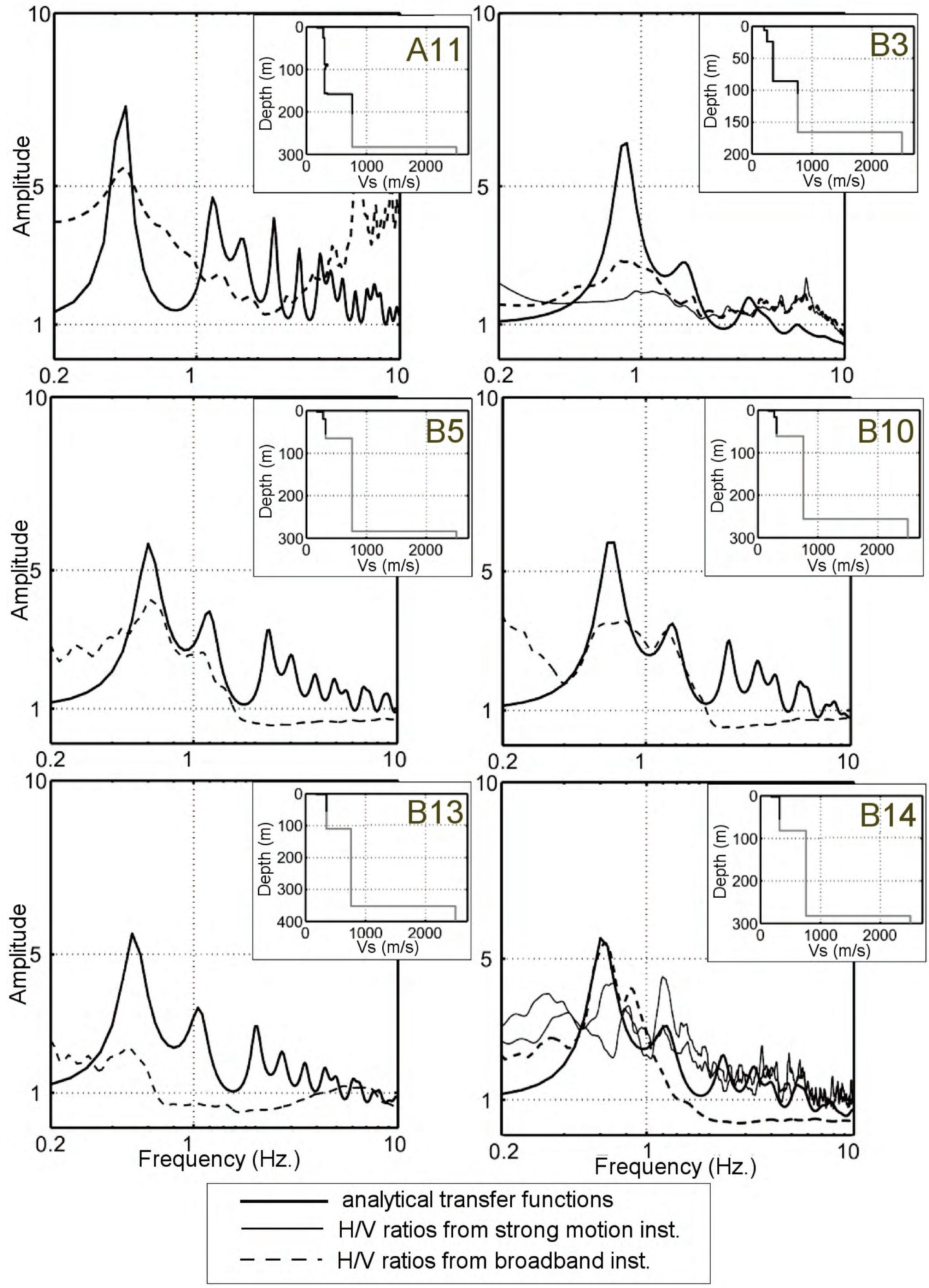

Figure 5. Comparison between H/V spectral ratios from microtremor measurements at A11, B3, B5, B10, B13, B14 sites. Inset figures show the 1D Velocity-depth profiles at the borehole locations. Dark line of the profiles shows the borehole results, and grey lines are calculated results.

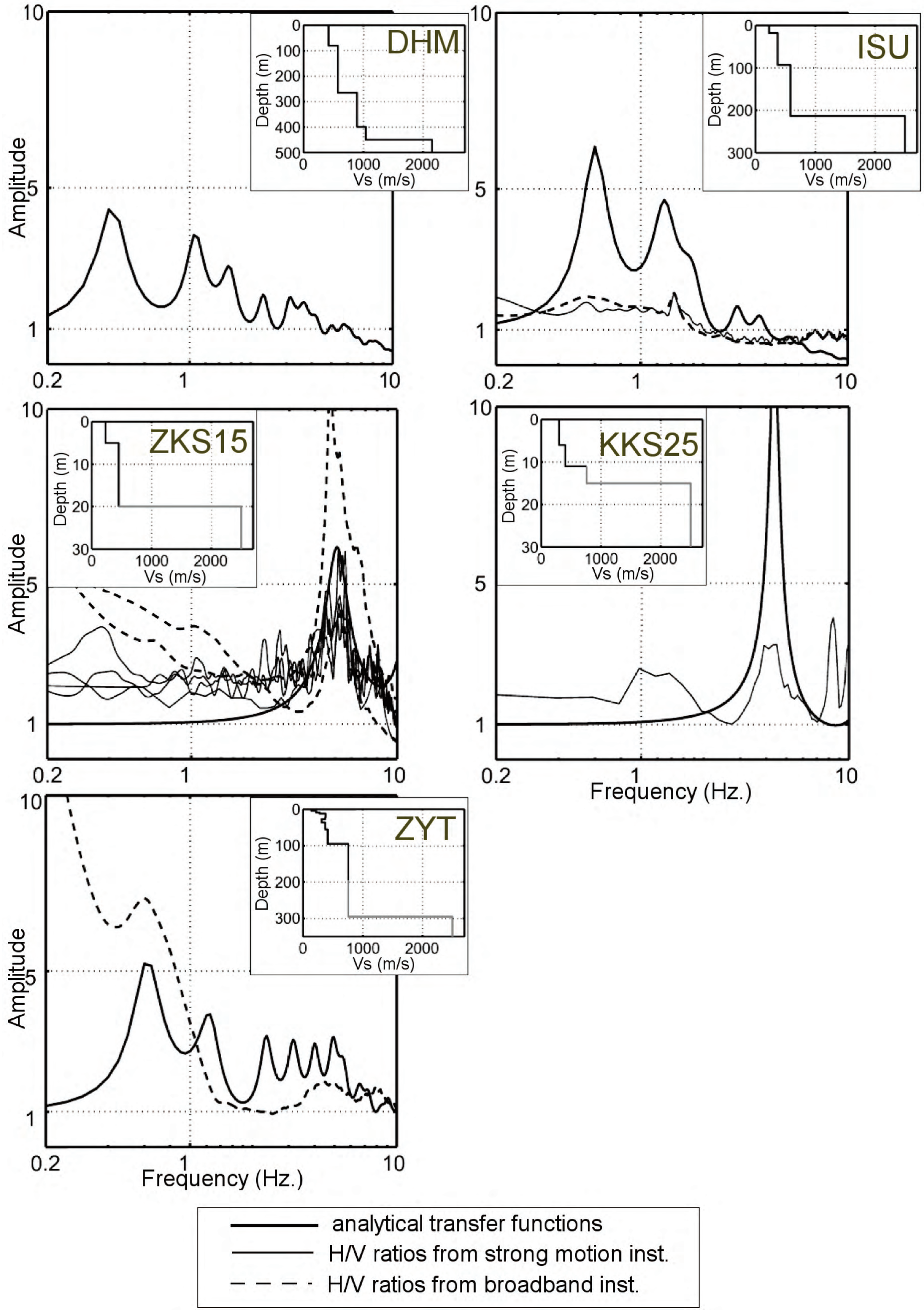

Figure 6. Comparison between H/V spectral ratios from microtremor measurements at DHM, ISU, ZKS15, KKS25, ZYT sites. Inset figures show the 1D Velocity-depth profiles at the borehole locations. The dark line of the profiles shows the borehole results, and grey lines are calculated results. Profiles of ISU and DHM are determined from microtremor array measurements of Kudo *et al.* (2002) and Özel *et al.* (2004), respectively.

column of visco-elastic layers of infinite horizontal extent. It is based on the continuous solution to the wave-equation adapted for use with transient motions through the Fast Fourier Transform. Nonlinearity of the shear modulus and damping is accounted for by the use of equivalent linear soil properties (Idriss & Seed 1968; Seed & Idriss 1970) using an iterative procedure to obtain values of modulus and damping which are compatible with the effective strains in each layer. The formations in the boreholes were accepted to be compatible with the formations for which degradation curves (G/G_{max}) are defined from Vucetic & Dobry (1991) relationships. For clayey soils, the G/G_{max} and damping curves proposed by Vucetic & Dobry (1991) were used and for alluvial or sandy soils the curves of Seed & Idriss (1970) were used. Excitation from the Palaeozoic bedrock was provided by a simple Ricker wavelet with a central frequency of 4 Hz.

The thickness of the engineering bedrock layer was determined by computing analytical transfer functions to fit the resonance frequency and shape of experimental transfer functions. By extending the thickness of engineering bedrock between 10–250 m, position of the resonance frequencies was caught. No depth adjustment was done for borehole sites ZKS 15 and KKS 25, since the deeper core samples confirm the existence of Palaeozoic bedrock. Analytical transfer functions for microtremor array measurement sites DHM and ISU (see Figure 2 for the locations) were calculated with direct use of thickness and velocity information given in Özel *et al.* (2004) and Kudo *et al.* (2002), respectively.

In order to further confirm the resonance frequencies of borehole sites, site transfer functions were also calculated using Haskell's (1953, 1960) method. The resulting frequencies obtained by this method show no significant deviation from those calculated using the Shake91 code.

Figures 4–6 show the calculated transfer functions compared with H/V spectra from strong motion and broadband instruments at 17 sites.

Resonance Frequency-Cover Thickness Relationship

In order to have a quantitative interpretation of the relationship between resonance frequency and cover thickness, an estimate was derived from the measured H/V peak frequencies. Assuming that the origin of the H/V spectral ratio resonance peak is related to S-wave resonances in a single sediment layer over half space (Nakamura 1989); the layer thickness can be related to the H/V resonance peak frequency as

$$f r = n \frac{Vs}{4h} \quad n = (1,3,5,\ldots) \qquad (2)$$

where *Vs* is the S-wave velocity of the sediment layer. A better approximation for the depth distribution of the S-wave velocity is a power law of the form:

$$Vs(z) = Vso(1+Z)^{x} \qquad (3)$$

Here, Z is the depth, *Vso* the S-wave velocity at the surface, Z= z/zo with zo= 1 m, and x describes the depth dependence of the velocity (Ibs-von Seht & Wohlenberg 1999; Scherbaum *et al.* 2003). In this case h can be derived from f_r by integrating the velocity function over the depth range and can be written as the form

$$h = a f_r^{b} \qquad (4)$$

Table 1. SPT-N blow counts and soil description for the formations in the study area.

SPT-N blow counts	Soil type	Unit weight (kN/m^2)	Shear Wave Velocity (m/sec)
5-20	GM-GC or CL	16.67-17.85	120-250
12-30	SM-SC or CL-CH	16.67-17.85	180-300
15-50	CH or MH	19.62-23.54	200-450
30-50	SM-SC	19.12-20.11	300-400
10-50	CL-CH	16.67-19.62	170-400
30-50	SM-SC	18.64-19.62	300-400
-	soft rock	19.62-26.00	250-500
-	strong rock	19.62-26.00	500-800
-	strong rock	19.62-25.00	400-700
-	CL-ML	16.67-19.62	300-400

Table 2. Site locations and resulting frequencies and cover thicknesses used to derive Equation 5.

Site Name	Latitude (N)	Longitude (E)	Resulting Frequencies (Hz)	Boring depth (m)	Soil thickness (m)
A3	40.979	28.774	0.44	106	366
A4	40.970	28.795	0.8	106	214
A5	41.034	28.791	1.54	106	116
A7	41.026	28.849	1.38	87	137
A8	40.979	28.826	0.6	106	222
A10	41.024	28.893	1.25	106	140
A11	40.974	28.736	0.46	206	283
B3	40.983	28.746	0.44	106	166
B5	41.003	28.781	0.66	56	284
B10	41.012	28.832	0.7	56	256
B13	40.961	28.837	0.47	56	352
B14	41.000	28.864	0.64	56	282
ZYT	40.986	29.908	0.63	195	295
ZKS15	40.993	29.076	5	20	20
KKS25	40.985	29.092	4.5	20	20
ISU	40.991	28.723	0.56	Microtremor	213
DHM	40.964	28.813	0.4	Array Measurement	449

H/V ratios from 15 measurements at the borehole locations and velocity profiles of 2 microtremor array measurement sites were used to derive such a relationship. From these data, a nonlinear relationship (Figure 7) between cover thickness (*H*) and resonance frequency of site (f_r) is found and a and *b* values in Equation (4) were calculated as

$$H = 150.99 f_r^{-1.1531} \quad (5)$$

Statistically the R^2 value is 99.5%, indicating a strong relationship between the frequency and thickness. The figure also displays 95% confidence limits for the true mean values of the thickness in the form of bounds around the regression line. The bounds are close to the regression line confirming the strong relationship indicated by the R^2 value.

The resulting resonance frequencies and cover thicknesses of 17 sites found by site response analysis are summarized in Table 2. Cover thicknesses vary between 20–449 m, where deepest covers correspond to sites located in the southwestern part of the city (at sites DHM, B13 and A3).

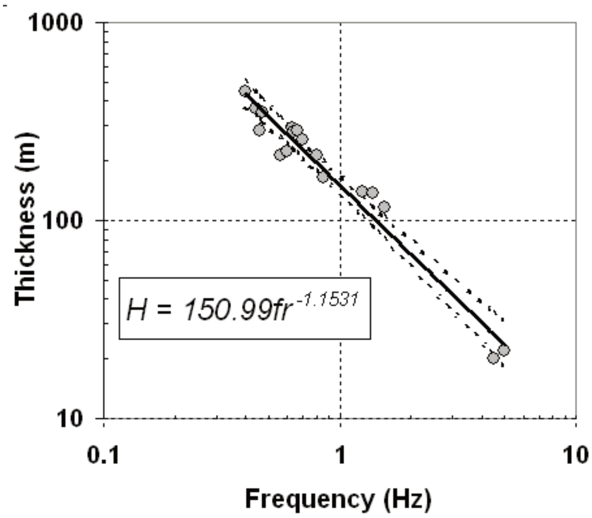

Figure 7. Empirical relationship between resonance frequency and the thickness of cover overlying bedrock in the İstanbul region. The solid line is the nonlinear fit to the data points according to Equation 5. Dashed lines indicate 95% confidence limits for the true mean values of the thickness.

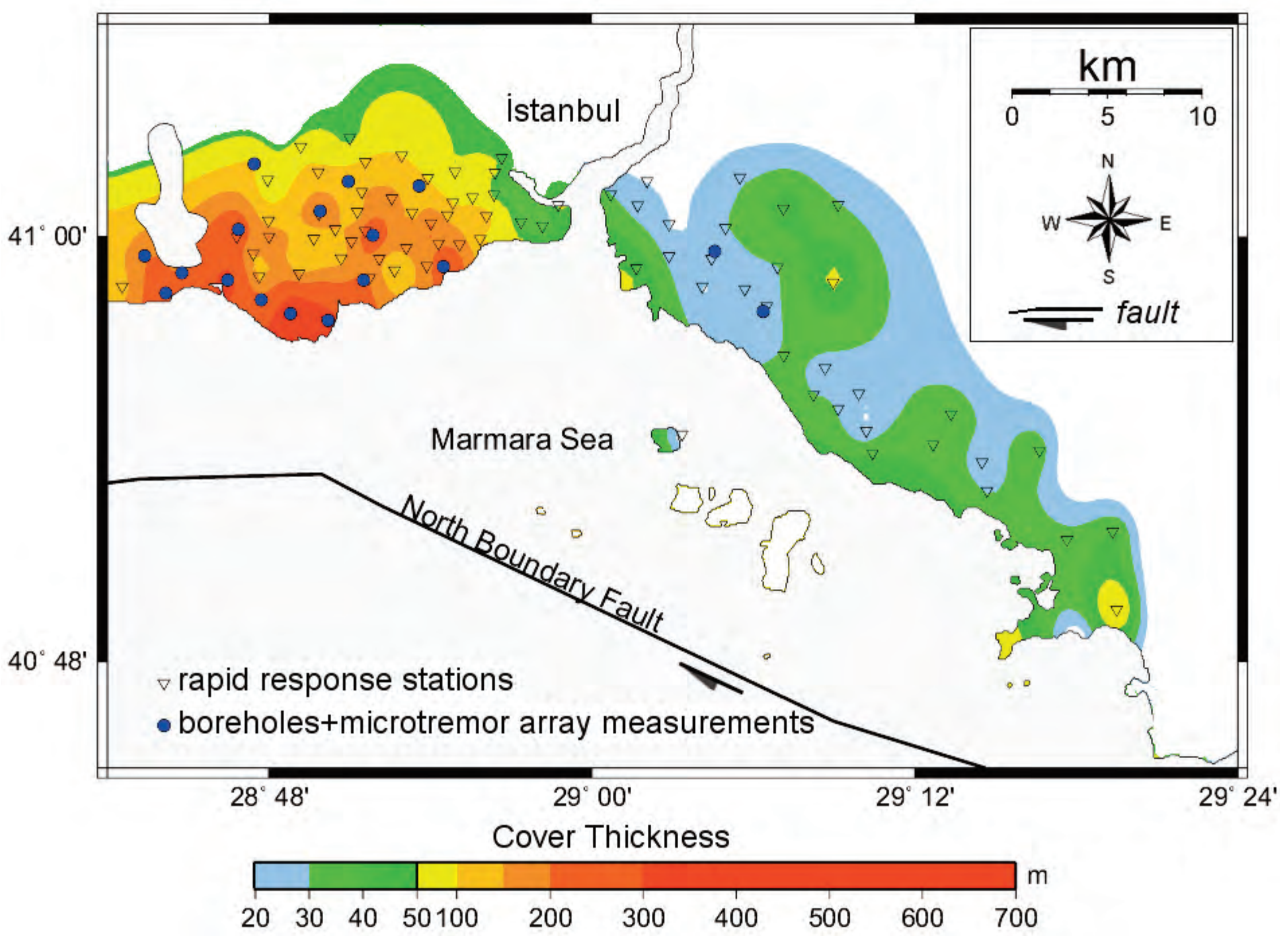

Figure 8. Distribution of soil thicknesses overlying Palaeozoic bedrock is derived by using the derived empirical relationship. Triangles and blue dots show, respectively, the location of RR stations and Boreholes & Microtremor array measurement sites used in the study. The closest active fault with very high seismic hazard is also shown.

As mentioned previously, a large number of single station seismic noise measurements have been carried out in İstanbul, allowing mapping of the resonance frequency distribution (Birgören & Özel 2006). Using those values in Equation 5, cover thickness overlying the bedrock in a wider area of İstanbul were calculated. Figure 8 depicts the cover thickness distribution beneath İstanbul city. Some of the remarkable points of the resultant map can be summarized as follows;

It is clear from Figure 8 that the distribution of the cover thickness increases towards the Sea of Marmara where upper Miocene–Pliocene sediments overlie older ones. Especially in the western part of the city, the resultant resonance frequency distribution and cover thickness map from these measurements are in remarkable agreement with surface geology information. Sites in the European side of İstanbul, geologically consisting of younger formations, have thicker covers compared to those located on the Asian side. The thickest cover (449 m) occurs in the southwest part of the city. Site effects are expected to be of particular concern in this region in the event of a strong earthquake. Thickness of cover increases from north towards the Marmara Sea in this region.

Discussion

During the 1999 Kocaeli earthquake, significant site amplification was observed to locally modify the ground motion in the metropolitan area. In particular, as shown by several studies (e.g., Cranswick *et al.* 1999; Ergin *et al.* 2004; Özel *et al.* 2004), the Avcılar district in western İstanbul (region where an ISU station and A11 borehole site were deployed) suffered significant damage, largely due to the amplification of the earthquake ground motion. As can be seen from Figure 1, there is a quite good correlation between the areas damaged by the 1999 Kocaeli earthquake and the distribution of the resonance frequencies; resonance frequencies measured in the damaged areas are mostly below 2 Hz, reflecting thicker sediment cover beneath these areas. Cranswick *et al.* (1999) studied the correlation between site response and building response immediately after the earthquake. To estimate this correlation they calculated the N–S and E–W horizontal building responses, and the radial and tangential horizontal site responses. Both N–S and E–W components of the building response exhibit peaks between 2–3 Hz as would be expected of the fundamental mode of a 5–6 storey building (assuming a period of about 0.1 s per floor). This frequency range is very close to resonance frequencies measured in this area. However, they also observed large amplitude phases after S-waves in the frequency band of about 0.25 Hz, and suggested that these large amplitude phases might be related to body wave/surface wave conversion because of topographical conditions, and/or to higher mode surface-wave amplification from the thickening of low-velocity layers. This finding may explain why less/no damage occurred in the other areas of İstanbul having the same resonance frequencies (>1Hz; Figure 1). These interpretations, suggested both in this study and in the other studies (e.g., Cranswick *et al.* 1999), need to be verified by more detailed studies.

This study is the first attempt to derive the bedrock depth map of İstanbul using limited geophysical data. The accuracy of resonance frequency-sediments thickness relationship obtained in the current study is highly dependent on the limited amount of borehole data in our knowledge available for İstanbul. Simplification of material properties at each representative soil profile is another important factor that affects the accuracy. It is intended to improve the depth resolution by proceeding with more detailed 1D modelling that will be available for the European side of the city in the near future.

Conclusion

In this paper an empirical relationship between the resonance frequency and cover thickness was derived using the geotechnical information from 15 available boreholes and resonance frequencies of H/V spectra estimated from single microtremor measurement at borehole sites. Velocity structure information of 2 microtremor array measurement sites were also utilized into the study. 1D site response analysis was performed at each borehole site considering representative soil profiles. Analytical transfer functions were fitted to the resonance frequency and the shape of experimental transfer functions by changing the thickness of engineering bedrock. The resulting cover thickness and frequency information could be derived as a nonlinear equation. The cover thickness across most of the city was then calculated by the newly derived relationship using the resonance frequencies previously determined at 86 RR sites distributed across the city. It has been observed that sites in the European side of İstanbul, geologically consisting of younger formations, have thicker covers than those on the Asian side. The thickest cover (449 m) is in the southwest part of the city.

The results are believed to improve the accuracy of strong motion estimations for İstanbul, particularly the ground motion predictions for regions located on thick soil deposits. It will motivate research groups to perform further geotechnical experiments to provide more refined models particularly in the southwest of the city.

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References

BARD, P.Y. 1999. Microtremor measurements: a tool for site effect estimation? *In:* IRIKURA, K., KUDO, K., OKADA, H. & SASATAMI, T. (eds), *The Effects of Surface Geology on Seismic Motion*. Balkema, Rotterdam, 1251–1279.

BARD, P.Y. & BOUCHON, M. 1980. The seismic response of sediment-filled valleys. I. The case of incident SH-waves. *Bulletin of Seismological Society of America* 70, 1263–1286.

BIRGÖREN, G. & ÖZEL, O. 2006. Determination of site effects and ground motion lengthening in İstanbul area derived from small earthquake recordings. *In*: *Proceedings of 8th US National Conference on Earthquake Engineering, San Francisco, 8NCEE-001908.*

BORCHERDT, R.D. 1970. Effects of local geology on ground motion near San Francisco Bay. *Bulletin of Seismological Society of America* 60, 29–61.

CRANSWICK, E., ÖZEL, O., MEREMONTE, M., ERDİK, M., ŞAFAK, E., MUELLER, C., OVERTURF, D. & FRANKEL A. 1999. Earthquake damage, site response, and building response in Avcilar, west of İstanbul, Turkey. *In*: *Proceedings of ITU-IAHS International Conference on the Kocaeli Earthquake, 17 August 1999,* ISBN 975-561-166-5, 193–204.

DELGADO, J., LÓPEZ C.C., GINER, J., ESTÉVEZ, A., CUENCA, A. & MOLINA, S. 2000. Microtremors as a geophysical exploration tool: applications and limitations. *Pure and Applied Geophysics* 157, 1445–1462.

ERGİN, M., ÖZALAYBEY, S., AKTAR, M. & YALÇIN, M.N. 2004. Site amplification at Avcılar, İstanbul. *Tectonophysics* 391, 335–346.

HASKELL, N.A. 1953. The dispersion of surface waves on multilayered media. *Bulletin of Seismological Society of America* 43, 17–34

HASKELL, N.A. 1960. Crustal reflection of plane SH waves. *Journal of Geophysical Research* 65, 4147–4150.

HINZEN, K.G., WEBER, B. & SCHERBAUM, F. 2004. On the resolution of H/V measurements to determine sediment thickness, a case study across a normal fault in the lower Rhine embayment, Germany. *Journal of Earthquake Engineering* 8, 909–926.

IBC 2006. *International Building Code*. International Code Council.

IBS-VON SEHT, M. & WOHLENBERG, J. 1999. Micortremor measurements used to map thickness of soft soil sediments. *Bulletin of Seismological Society of America* 89, 250–259.

IDRISS, I.M. & SEED, H.B. 1968. Seismic response of horizontal layers. *Journal of the Soil Mechanics and Foundations Division, ASCE* 94, 1003–1031.

IDRISS, I.M. & SUN, J.I. 1992. *User's Manual for SHAKE91: A Computer Program for Conducting Equivalent Linear Seismic Response Analyses of Horizontally Layered Soil Deposits*. Center for Geotechnical Modeling, University of California, Davis.

İSTANBUL GOVERNORATE, Disaster Management Center, 1999.

İYİSAN, R. 1996. Correlations between shear wave velocity and in-situ penetration test results. *Technical Journal of Turkish Chamber of Civil Engineers* 7, 1187–1199 [in Turkish with English abstract].

JICA & IMM (Japan International Cooperation Agency & İstanbul Metropolitan Municipality) 2002. *The Study on a Disaster Prevention/Mitigation Basic Plan in İstanbul Including Seismic Microzonation*. Field Report (2) Appendix1.

KAWASE, H. 1996. The cause of the damage belt in Kobe: 'the basin-edge effect', constructive interference of the direct S-wave with the basin induced diffracted Rayleigh waves. *Seismological Research Letters* 67, 25–34.

KUDO, K., KANNO, T., OKADA, H., ÖZEL, O., ERDİK, M., SASATANI, T., HIGASHI, S., TAKAHASHI, M. & YOSHIDA, K. 2002. Site-specific issues for strong ground motions during the Kocaeli, Turkey, earthquake of 17 August 1999, as inferred from array observations of microtremors and aftershocks. *Bulletin of Seismological Society of America* 92, 448–461.

MAYNE, P.W. & RIX, G.J. 1995. Correlations between shear wave velocity and cone tip resistance in natural clays. *Soils and Foundations* 35, 107–110.

NAKAMURA, Y. 1989. A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. *Quarterly Report of Railway Technical Research Institute (RTRI)* 30, 25–33.

OKAY, A.İ. 1986. Tectonic units and sutures in Pontides, Northern Turkey: tectonic evolution of the Tethyan Region. *NATO ASI Series* C259, 109–116.

OKAY, A.İ., KAŞLILAR-ÖZCAN, A., İMREN C., BOZTEPE-GÜNEY, A., DEMİRBAĞ, E. & KUŞÇU, İ. 2000. Active faults and evolving strike-slip basins in the Marmara Sea, northwest Turkey: a multichannel seismic reflection study. *Tectonophysics* 321, 189–218.

OHTA, Y. & GOTO, N. 1978. Empirical shear wave velocity equations in terms of characteristics soil indexes. *Earthquake Engineering and Structural Dynamics* 6, 167–187.

ÖZEL, O., BIRGÖREN, G. FAHJAN, Y., ALÇIK, H. & ERDİK, M. 2006. *İstanbul Deprem Acil Müdahale ve Erken Uyarı Sisteminin Kalibrasyonu ve İstasyon Yerlerinin Depreme Karşı Yerel Tepkilerinin Belirlenmesi* [*Determination of Site Response and Calibration of İstanbul Early Warning and Rapid Response Stations]*. BU-SRP Project no. 05T102 [in Turkish, unpublished].

ÖZEL, O., CRANSWICK, E., MEREMONTE, M., ERDİK, M. & ŞAFAK, E. 2002. Site effects in Avcılar, west of İstanbul, Turkey, from strong- and weak-motion data. *Bulletin of Seismological Society of America* 92, 499–508.

ÖZEL, O., SASATANI, T., KUDO, K., OKADA, H., KANNO, T., TSUNO, S., YOSHIKAWA, M., NOGUCHI, S., MIYAHARA, M. & GOTO, H. 2004. Estimation of S-wave velocity structures in Avcılar-İstanbul from array microtremor measurements. *Journal of the Faculty of Science, Hokkaido University 7, Geophysics* 12, 115–129.

PAROLAI, S., BORMANN, P. & MILKERT, C. 2002. New relationships between Vs, thickness of sediments, and resonance frequency calculated by the H/V ratio of seismic noise for Cologne Area (Germany). *Bulletin of Seismological Society of America* 92, 2521–2527.

PARSONS, T., TODA, S., STEIN, R.S., BARKA, A. & DIETERICH, J.H. 2000. Heightened odds of large earthquakes near İstanbul: An interaction-based probability calculation. *Science* 288, 661–665.

SCHERBAUM, F., HINZEN, K.G. & OHRNBERGER, M. 2003. Determination of shallow shear wave velocity profiles in the Cologne, Germany area using ambient vibrations. *Geophysics Journal International* **152**, 597–612.

SCHNABEL, P.B., LYSMER, J. & SEED, H.B. 1972. *SHAKE-A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites*. Report no. **EERC 72–12**, University of California, Berkeley.

SEED, H.B. & IDRISS, I.M. 1970. *Soil Moduli and Damping Factors for Dynamic Response Analyses*. Report no. **EERC 70–10**, EERC, University of California, Berkeley.

SORENSEN, M.B., OPRSAL, I., BONNEFOY-CLAUDET, S., ATAKAN, K., MAI, M., PULIDO, N. & YALÇINER C. 2006. Local site effects in Ataköy, İstanbul, Turkey, due to a future large earthquake in the Marmara Sea. *Geophysics Journal International* **167**, 1413–1424.

VUCETIC, M. & DOBRY, R. 1991. Effects of soil plasticity on cyclic response. *Journal of Geotechnical Engineering, ASCE* **117**, 89–107.

WALD, D.J. & GRAVES, R.W. 1998. The seismic response of the Los Angeles Basin, California. *Bulletin of Seismological Society of America* **88**, 337–356.

WESSEL, P. & SMITH, W.H.F. 1998. New, improved version of Generic Mapping Tools released. *EOS Transactions.* AGU **79**, p. 579.

YILDIRIM, M. & SAVAŞKAN, E. 2003. A new approach to statigraphy of tertiary sediments at İstanbul and their engineering properties. *In: Proceedings of Geology of İstanbul*. The Chamber of Geological Engineers Publication, 87–102 [in Turkish with English abstract].